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Experimental investigations of coal dust-inertant mixture explosion behaviors

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Abstract

An experimental investigation was carried out on coal dust-inertant mixture explosions. Tests of explosion severity and flammability limit were conducted by using the Siwek 20 L vessel and influences of ignition energy, coal dust calorific value, coal dust concentration and inertant composition were taken into account. The increase of inerting results with ignition energy is followed by an approximate stabilization when ignition energy exceeds 5 kJ. The ignition energy region of 5-10 kJ is appropriate for inerting testing, whereas ignitors with energy lower than 5 kJ produce unrealistic inerting results. The inerting effectiveness of inertant increases with the reduction of coal dust calorific value. Coal dust concentrations near the stoichiometric concentration require the greatest amount of inertant to suppress explosions. As the coal dust concentration increases beyond the stoichiometric, the amount of inertant requirement is reduced. Due to the efficient decomposition and particular flame extinguishing mechanism, monoammonium phosphate represents more excellent inerting effectiveness than calcium carbonate.

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Keywords: Coal dust; Dust explosion; Inerting; Ignition energy

1. Introduction

Coal dust-inertant mixture is widespread in the industrial production. Inering, i.e. to mix the combustible coal dust with inertant, is considered as an inherent safety approach[1]. This principle has been practiced in underground coal mining where rock dusts are mixed with coal dust to prevent

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explosions. Other applications do exist, for example, inertant is usually added into the pulverized coal to reduce the explosion frequency in the coal pulverizing system of blast furnaces. Nevertheless, although the mentioned countermeasures have been carried out, coal dust explosions still represent significant damages in mining, metallurgy and energy industries. As far as China is concerned, a large number of accidents happened with losses of human lives and destruction of industrial facilities[2,3]. Therefore it is urgent to increase the understanding of coal dust-inertant mixture explosions.

Several studies were carried out on this field and data in previous article mostly focused on the effect of inertant mixing ratio on the coal dust explosion severity[4-8]. Unfortunately, few studies included a systematic study showing influences of coal dust concentration and coal dust calorific value, above all, influence of ignition energy is hardly mentioned.

This work aims to present data about the overall characteristics of coal dust-inertant mixture ignitability and explosibility. Information about the fully inerting content FIC and explosion severity (maximum explosion pressure p_{max} and maximum rate of pressure rise $(dp/dt)_{max}$) was given. Influences of some factors, such as ignition energy, coal dust calorific value, coal dust concentration and inertant composition, were analyzed. Moreover, the inerting effectiveness of different inertants was compared.

2. Materials and experimental setups

Two samples of coal dust were prepared by milling and sieving the purchased cleaned coal. Their particle size distributions and calorific values were illustrated in Table 1. The calorific value was determined by DDS Cal 2k oxygen bomb calorimeter. In the inerting work, calcium carbonate and monoammonium phosphate were chosen as inertants. The wide use of rock dusts consisting of limestone in coal mining industries gives the idea that calcium carbonate can be applied to prevent or mitigate coal dust explosions. Monoammonium phosphate shows a potential of inerting because it is widely used as the powder extinguishing agent. The combustible-inert mixtures were well-mixed before testing. All the samples were systematically dried at 50 ℃ for 2 hours before handling.

Table 1 Properties of tested coal dust samples

Coal samples	Particle size distribution (μm)	Calorific value (kJ/g)
Sample A	75-125	20.06
Sample B	75-125	30.97

Experiments were performed in the well-known 20 L sphere developed by Siwek[9] initially (Fig.1). The vessel is an explosion resistance hollow sphere made of stainless steel with a volume of 20 L in accordance with the recommendations of European standard EN 14034[10-12], ASTM standard E1226[13] and Chinese standard GB/T 16425[14]. Dust clouds in the vessel are ignited by pyrotechnical ignitors. The ignition energy depends on the mass of pyrotechnical composition which consists of zirconium, barium nitrate and barium dioxide by 4:3:3 by weight.

Table 2 Evolutions of pressure rise due to ignitors with ignition energy

Ignition energy (kJ)	1	2	5	10
Pressure rise due to ignitors (MPa)	0.01	0.02	0.07	0.12

Heat liberated by ignitors would directly lead to a pressure rise $p_{ignitor}$. In the present work, $p_{ignitor}$ was picked out by determining pressure rise due to ignitors themselves without adding coal dust samples. Table 2 shows that $p_{ignitor}$ is somewhat proportional to ignition energy.

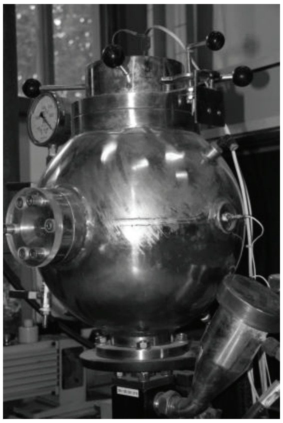

Fig.1 Siwek 20 L vessel

For a given test, the test chamber was sealed and partly evacuated to -0.06 MPa. The computer control program was initiated and the dust storage was pressurized to 2.0 MPa. Then the solenoid valve was opened and the dust-air mixtures were dispersed into the test chamber, raising its pressure to the standard atmospheric pressure. The computer energized the ignitor after a delay of 60 ms and recorded the pressure-time history of an explosion. The pressure-time trace can provide values of total pressure rise p_{ex} and $(dp/dt)_{max}$. It should be pointed out that the value of p_{max} was obtained by subtracting $p_{ignitor}$ from p_{ex}. Values of p_{max} are typically related to the thermodynamics concerned with the amount of heat liberated during combustion, whereas $(dp/dt)_{max}$ is concerned with the rate at which the reaction heat is liberated[15]. Three replications were performed at each set of experimental conditions and data presented in this work was presented by means of average values.

3. Results and discussion

3.1. Pressure development of coal dust-inertant mixtures

Different actions of pressure development under various inertant mixing ratios were obtained. Data obtained with coal dust concentration of 250 g/m^3 was picked out for a typical discussion. The explosion pressure-time traces of Sample B-calcium carbonate mixtures and Sample B-monoammonium phosphate mixtures were plotted in Figs.2 and 3 respectively. As can be seen, two characteristics were identified. On one hand, p_{max} decreases with the rise of inertant mixing ratio, which means that the explosion energy is diminished. On the other hand, the decrement of trace slope at higher inertant mixing ratio means that the reduction of burning velocity with the rise of inertant mixing ratio is verified.

According to the flame propagation mechanism of coal dusts[16,17], the flame propagation starts with the devolatilization followed by a vapor-phase combustion. Inertant suppresses coal dust explosions by absorbing combustion heat from burning particles[8]. The temperature reduction prevents further devolatilization of unburned particles[18]. As a result, the volatile concentration gets lower and there is neither sufficient fuel nor heat to sustain the flame propagation[7]. Moreover, the inert gas (such as carbon dioxide and ammonia) decomposed from inertant results in higher resistance in oxygen diffusion[19] and thereby it might be an alternative reason.

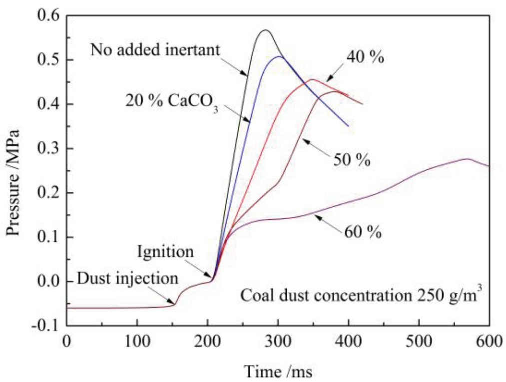

Fig.2 Traces of pressure-time under various $CaCO_3$ mixing ratios, for coal sample B with the concentration of 250 g/m^3

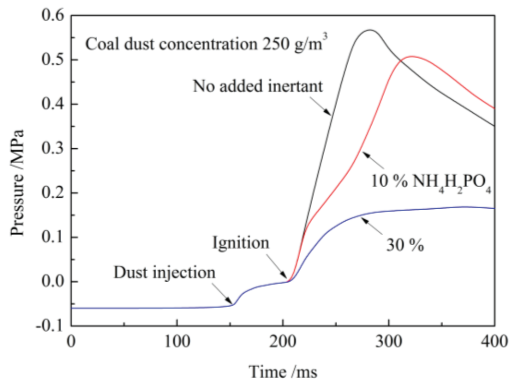

Fig.3 Traces of pressure-time under various $NH_4H_2PO_4$ mixing ratios, for coal sample B with the concentration of 250 g/m^3

3.2. Influence of ignition energy

The effect of ignition energy was conducted on Sample A-calcium carbonate mixtures. Tests were carried out under four ignition energies of 1, 2, 5 and 10 kJ, with coal dust concentration of 500 g/m^3. Evolutions of p_{max} and $(dp/dt)_{max}$ were plotted as functions of inertant mixing ratio for various ignition energies (Figs.4 and 5). As expected, p_{max} and $(dp/dt)_{max}$ decrease with the rise of inertant mixing ratio for all ignition energies involved. It is essential to point out that 5 and 10 kJ ignitors yield the similar inerting level while the results of 1, 2 and 5 kJ vary from each other significantly.

The FIC was obtained by determining the inerant mixing ratio where each p_{max}-ignition energy curve illustrated in Fig.4 crosses the explosion criterion. The explosion criterion $p_{max} \geqslant 0.03$ MPa were advocated by both EN 14034-3[12] and GB/T 16425[14]. Results of FIC were plotted in Fig.6. The typical pattern of variation with ignition energy was observed and especially the increase of FIC from 1 kJ up to 5 kJ, followed by an approximate stabilization for higher ignition energy.

In the previous study of authors' group, it was found that values of both p_{max} and $(dp/dt)_{max}$ increase sharply with ignition energy varying form 1 to 5 kJ, whereas show a stabilization when ignition energy ranges from 5 to 10 kJ[6,20,21]. This is because the volatile yields of coal dusts are related to the strength of ignition sources[22]. Ignitiors with energy lower than 5 kJ may yield unrealistic results because weak ignitors will underdrive the coal dust explosions, that is, explosions initiated with weak ignition energy cannot yield sufficient volatile to make efficient flame propagation. Thus the ignition region of 5-10 kJ may be more appropriate for coal dust explosion testing.

An additional minimum explosion concentration MEC testing was carried out for pure coal dusts (Fig.6). The stabilization of MEC is identified when ignition energy ranges from 5 to 10 kJ. Cashdollar[23], Going[24] and Hertzberg[25] advocated that realistic MEC should be determined under conditions where it is independent of ignition energy. Considering that an analogy has been drawn between FIC and MEC because both of them are flammability limit parameters[26], the realistic FIC should also be relatively independent of ignition energy. Consequently energy region of 5-10 kJ is the most appropriate for FIC determination. Ignitors with energy lower than 5 kJ are inappropriate, because the corresponding result is far away from the stabilization. The weak ignition energy yields overly low FIC, which will provide invalid guidance for safe design of suppression and chemical barrier systems. Moreover, ignitors with energy higher than 10 kJ are also inappropriate. The overly strong ignition energy may burn the dust cloud within the flame of ignitors, even though the dust cloud could not sustain a self-sustained flame propagation[27].

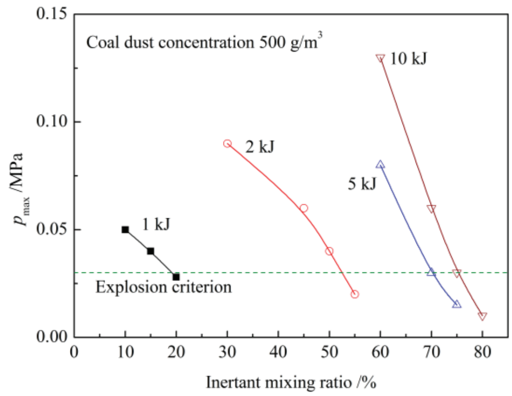

Fig.4 Evolutions of p_{max} with $CaCO_3$ mixing ratio under various ignition energies, for coal sample A with the concentration of 500 g/m^3

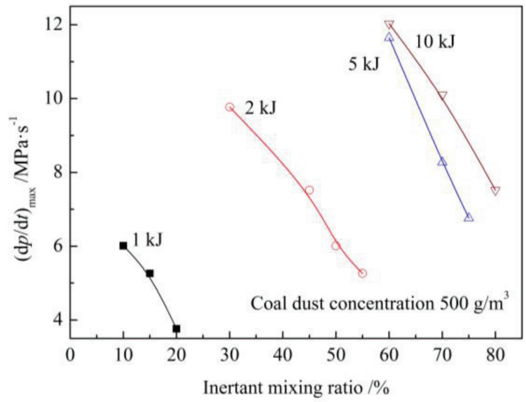

Fig.5 Evolutions of $(dp/dt)_{max}$ with $CaCO_3$ mixing ratio under various ignition energies, for coal sample A with the concentration of 500 g/m^3

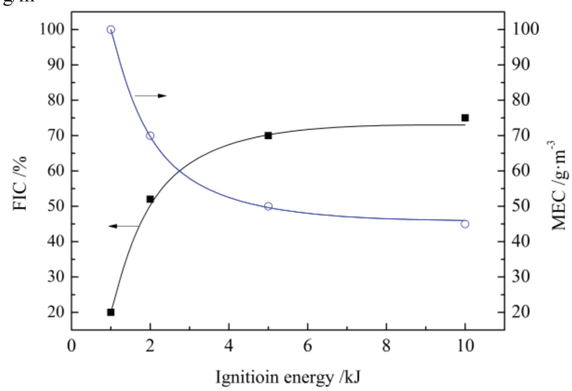

Fig.6 Evolutions of FIC and MEC with ignition energy

3.3. Influence of coal dust calorific value

The effect of coal dust calorific value was conducted on Sample A-calcium carbonate mixtures and Sample B-calcium carbonate mixtures. Tests were carried out at 5 kJ, with coal dust concentration of 500 g/m^3. Evolutions of p_{max} and $(dp/dt)_{max}$ were plotted as functions of inertant mixing ratio for each sample (Figs.7 and 8). Sample A represents similar p_{max} and $(dp/dt)_{max}$ to Sample B under the condition of no added inertant. For only 10 % inertant, values of p_{max} and $(dp/dt)_{max}$ drop to 0.28 MPa and 9.02 MPa/s for Sample A-calcium carbonate mixtures, which corresponds to yields of 62 % and 70 % of the pure coal results. Nevertheless, the corresponding results are 91 % and 76 % for Sample B-calcium carbonate mixtures. As the calorific value of coal dust is reduced, both p_{max} and $(dp/dt)_{max}$ diminish more significantly with the rise of inertant mixing ratio. This indicates that the inerting effectiveness of inertant increases with the reduction of coal dust calorific value, and coal dusts with higher calorific value require more inertant for inerting than lower calorific value coal dusts. This is because lower calorific value coal dusts usually have more ash content and the incombustible can act as a thermal sink helping to suppress explosions.

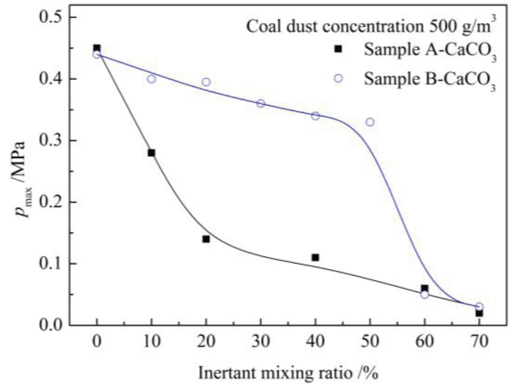

Fig.7 Evolutions of p_{max} with $CaCO_3$ mixing ratio, for coal samples A and B with the concentration of 500 g/m^3

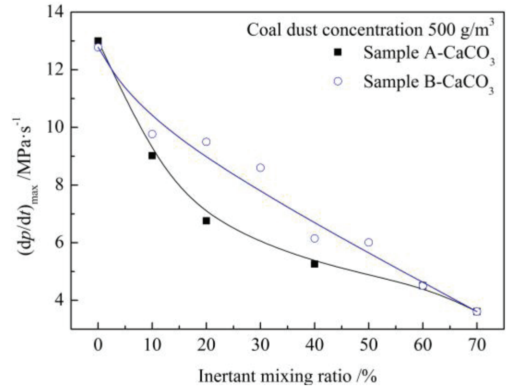

Fig.8 Evolutions of $(dp/dt)_{max}$ with $CaCO_3$ mixing ratio, for coal samples A and B with the concentration of 500 g/m^3

3.4. Influence of coal dust concentration

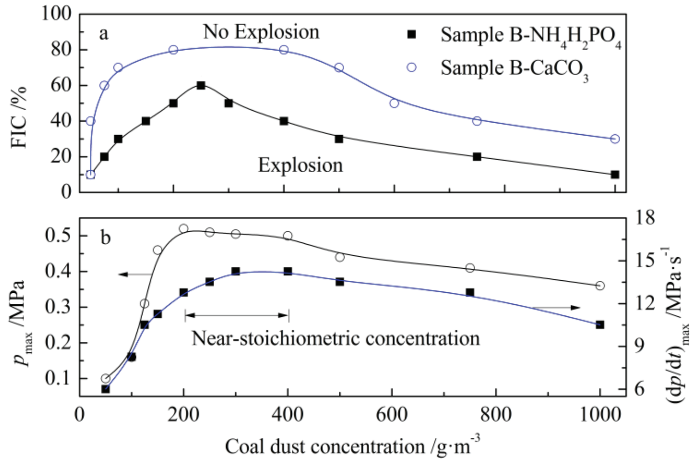

Fig.9. (a) Evolutions of FIC with coal dust concentration, for coal sample B-$CaCO_3$ and coal sample B-$NH_4H_2PO_4$ mixtures; (b) evolutions of p_{max} and $(dp/dt)_{max}$ with coal dust concentration, for pure coal sample B

The effect of coal dust concentration was conducted on Sample B-calcium carbonate mixtures and Sample B-monoammonium phosphate mixtures. Tests were carried out at 5 kJ, with coal dust concentration ranging from 50 to 1000 g/m^3. Values of FIC were plotted as functions of coal dust concentration for each sample in Fig.9a. As can be seen, FIC increases sharply with the rise of dust concentration for poorly loaded coal dust clouds up to about 200-400 g/m^3, followed by a decrease for highly loaded coal dust clouds. This is because the explosion reactivity is related to the volatile yield. The rise of coal dust concentration leads to the increase of the volatile. Hence the requirement of inertant to fully suppress an explosion increases with the coal dust concentration. The highest reactivity is always generated when the volatile reaches the near-stoichiometric concentration (Fig.9b), thus the inertant represents the worst inerting effectiveness. As the coal dust concentration exceeds the stoichiometric, more and more coal particles cannot be completely burning due to the oxygen deficiency and inefficient heat transfers with highly loaded coal dust clouds[28]. As a result, the unburned coal particles act as a thermal sink helping to suppress explosions; therefore the inertant requirement to fully suppress explosions is diminished.

3.5. Influence of inertant composition

A comparison of inerting effectiveness on explosion severity was performed between carbonate mixtures and monoammonium phosphate. Tests were carried out on Sample B using 5 kJ ignitors, with coal dust concentration of 250 g/m^3. Values of p_{max} and $(dp/dt)_{max}$ were plotted as functions of inertant mixing ratio for each sample in Figs.10 and 11. As can be seen, the inerting effectiveness of monoammonium phosphate appears to be much better than calcium carbonate. Values of p_{max} and $(dp/dt)_{max}$ decrease sharply with the rise of monoammonium phosphate content. For 30 % monoammonium phosphate, p_{max} and $(dp/dt)_{max}$ drop to 0.11 MPa and 6.01 MPa/s, which correspond to yields of only 22 % and 44 % of the pure coal results. Nevertheless, calcium carbonate represents worse effectiveness even when its mixing ratio reaches 60 %. Moreover, a comparison on FIC was also performed between Sample B-calcium carbonate mixtures and Sample B-monoammonium phosphate mixtures (Fig.9a). As expected, values of FIC of Sample B-monoammonium phosphate mixtures are always lower than those of Sample B-calcium carbonate mixtures for all coal dust concentrations involved, which means that better inerting effectiveness of monoammonium phosphate is corroborated again.

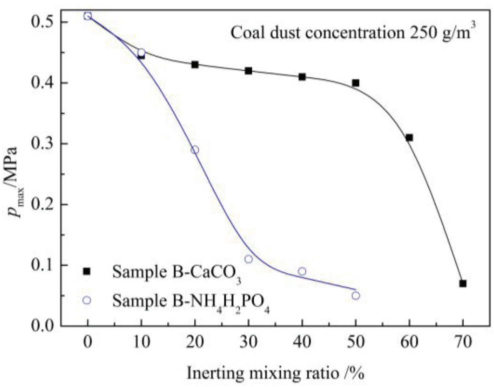

Fig.10 Evolutions of p_{max} with $CaCO_3$ and $NH_4H_2PO_4$ mixing ratios, for coal sample B with a concentration of 250 g/m^3

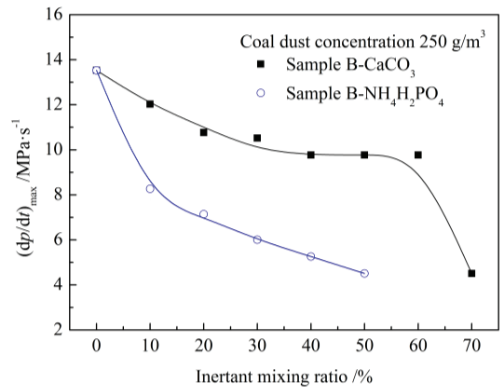

Fig.11 Evolutions of $(dp/dt)_{max}$ with $CaCO_3$ and $NH_4H_2PO_4$ mixing ratios, for coal sample B with a concentration of 250 g/m^3

The excellent inerting effectiveness of monoammonium phosphate is somewhat attributed to the follow three reasons. Firstly, the heat balance of fuel-inertant mixtures explosion addressed by Chatrathi[19] gives the idea that the decomposition plays a key role in the inerting effectiveness, which consistents with Abbasi[29]. The decomposition temperature of monoammonium phosphate (190 ℃) is much lower than that of calcium carbonate (950 ℃). Hence the efficient decomposition of monoammonium phosphate results in the excellent thermal sink. Secondly, the free ammonia decomposed from monoammonium phosphate has a particular efficacy in flame extinguishing[30].

Thirdly, the phosphorus pentoxide decomposed from monoammonium phosphate is prone to coating the burning particles, which results in higher resistance in the process of volatile yielding. Finally, it should be pointed out that neither calcium carbonate nor monoammonium phosphate is a very perfect inertant because both of them have to be added at a relatively high ratio to suppress coal dust explosions fully, and thereby more effective inertant needs further investigation.

4. Conclusions

The systematic study of coal dust-inertant mixture explosion behaviors has been conducted by using the Siwek 20 L vessel. As a consequence, influences of ignition energy, coal dust calorific value, coal dust concentration and inertant composition were investigated.

The influence of ignition energy has been emphasized in this study. The increase of inerting results with ignition energy ranging from 1 to 5 kJ is followed by an approximate stabilization for higher ignition energy. The ignition energy region of 5-10 kJ is appropriate for inerting testing, especially for fully inerting content determination. Ignitors with energy lower than 5 kJ produce unrealistic inerting results, because the realistic flammability parameter is relatively independent of ignition energy.

The inerting effectiveness of inertant increases with the reduction of coal dust calorific value. The more ash content in lower calorific value coal dust acts as thermal sick helping to suppress explosions, and therefore lower calorific value coal dust requires less inertant for inerting than higher calorific value one.

It emerges notably from this study that coal dust concentrations near the stoichiometric concentration where the peak values of maximum explosion pressure and maximum rate of pressure rise are reached for pure coal dusts require the greatest amount of inertant to suppress explosions. As coal dust concentration increases beyond the stoichiometric, the excessive coal particles act as inertant, therefore the inertant requirement is reduced.

Due to the efficient decomposition and particular flame extinguishing mechanism, monoammonium phosphate represents more excellent inerting effectiveness than calcium carbonate.

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